A Sequence Stratigraphic Analysis of Fluvio-Deltaic Deposits using Facies Characterization and Wireline Logs Correlation: Case of the Upper Devonian Tahara Formation, Ghadamis Basin, Libya

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Abstract: ***The correlation between wireline logs and sedimentological data can provide a better understanding of reservoir architecture and sandstone interconnectedness. In this paper, we present the application of wireline log correlation and core results for sequence stratigraphic analysis to the Upper Devonian Tahara Formation, Ghadamis Basin. Sequence stratigraphic analysis indicates that the Tahara Formation is characterised by transgressive and regressive phases of deposition in response to changes in relative sea level. The overall succession stacks into two partial sequences separated by a Type 1 sequence boundary. The lower sequence below the sequence boundary represents a coarsening-upward prograding shoreline comprising sediments deposited as part of a highstand systems tract. Above the sequence boundary, the incomplete sequence 2, includes the Tahara sandstones. These are believed to have been deposited as part of a transgressive systems tract bounded at the top by a maximum marine flooding surface. The succession includes marine flooding surfaces of different hierarchical level which record a deepening of the depositional environment in response to sea-level rise. Both preserved sequences form part of a third-order cycle which in the upper part includes fourth-order higher frequency cycles. The deposition and distribution of facies within the sequences are controlled by different factors including rate of relative sea-level change, rate of subsidence and sediment supply. Gamma ray log shapes in the Tahara sandstones vary from funnel to roughly cylindrical shapes. The lower Tahara sandstone shows a serrate cylindrical gamma ray log shape in well CI-49 and AST2, and a funnel gamma ray log shape in well K1-1, A1-NC151 and AST1. The upper Tahara sandstone shows a funnel gamma ray log shape in well CI-49, a complex gamma ray log shape in well K1-1 trend, and a serrate cylindrical gamma ray log shape in wells A1-NC151 and AST2.***

Keyword: Sequence stratigraphy. Sedimentology. Wireline logs. Siliciclastic

1. Introduction

The NC151 concession (Atshan Field) is located between the Ghadames basin to the north and Murzuq basin to south, some 200 km south of Tripoli. It is bounded by the latitudes, 26° 00' and 29° 00', and longitudes 10° 00' and 13° 00' (Figure 1). The stratigraphic architecture of the Silurian-Devonian succession has a significant impact on the distribution of oil and gasfields in Libya's Ghadames Basin.

The Ghadames basin is well known from numerous surface and subsurface studies in western Libya. It is filled by mainly Palaeozoic sediment overlain by a relatively thin Mesozoic-Tertiary sequence. Most of the Palaeozoic sediments consist of sandstones deposited in continental, transitional and marine environments. Palaeozoic sediments are thickest in the centre of the basin but thin gradually towards the southern margin of the basin which flanks the Al Gargaf arch (Hammuda 1980).

Sedimentological analysis indicates that the Tahara Formation (Upper Devonian-Lower Carboniferous) was deposited in shallow-water marginal and nearshore marine environments influenced by waves and storms. These are interpreted to represent interactive shelf to nearshore and fluvial deltaic environments (Rahmani 1994, Burki, 1998). Petrographic analysis of the same core showed the Tahara sandstone to consist of fine- to very fine-grained, well-sorted sandstone with low porosity and permeability due to the presence of abundant silica and calcite cement (Tawadros 1994).

The analysis and interpretation of the core succession allow seven facies to be recognised based on core and electric log data from type well CI-49, supplemented by core data and wireline log data from the other 5 wells (K1-1, A1-NC151, ATS1, ATS2 and B1-49) (Fig. 1). Each facies is identified on the basis of lithology, sedimentary structures and biogenic features. The first four facies have been grouped into a facies association (Table 1).

The main objectives of this study are to apply sequence stratigraphic methods to the Tahara Formation, using variations in facies tracts and stacking patterns in relation to changes in base level and to review the use of wireline logs in sequence stratigraphy and to define various characteristic log patterns, especially gamma ray patterns, and integrate them with the core data.

2. Methodology and data

This study is based on previous study (Burki 1998) which has been carried out on slabbed cores and has focused mainly on lithofacies analysis, vertical facies sequences, and lateral facies relationships between wells. Well CI-49 is considered the type well based on the core coverage of over 67 m across the entire Tahara Formation (Figure 2). Well ATS2 is the second most important well because it encountered the lower Tahara sandstone and therefore provides useful information on the lateral facies variations between these wells. The vertical relationships and characteristic sedimentary structures of each facies identified in the wells are presented in Table 1. The available information was integrated into a number of regional NE to SW oriented cross-sections (Figs. 4 and 6). Basic lithofacies, parasequences and parasequences sets were all interpreted from gamma/SP and resistivity/sonic log profiles and supported by inter-well correlations. However, the gamma ray log was the most useful for delineating facies geometries and depositional relationships. Depth of core and wireline logs are given in feet, and thickness of internal structures is given in both imperial and metric scales.

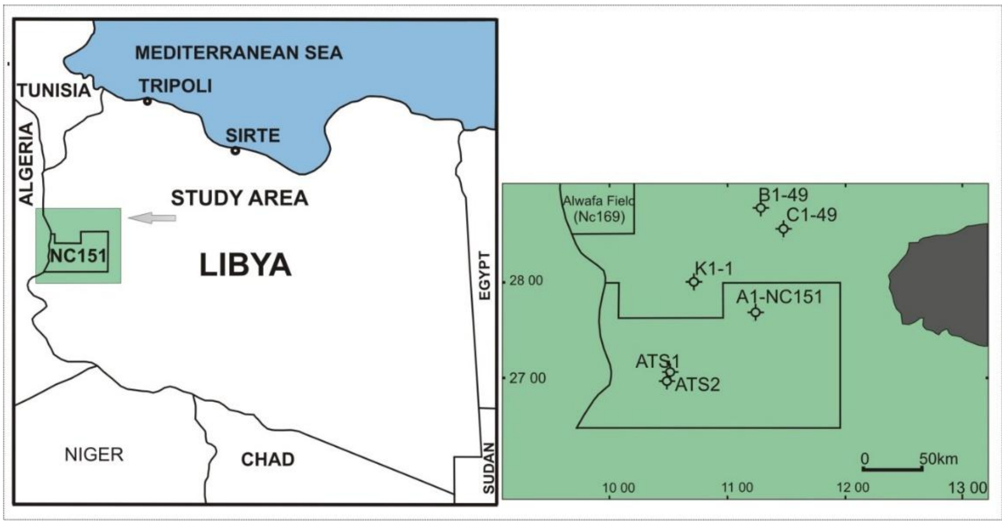

Figure 1: Location map of the area showing the location of the concession and the wells analysed in this study

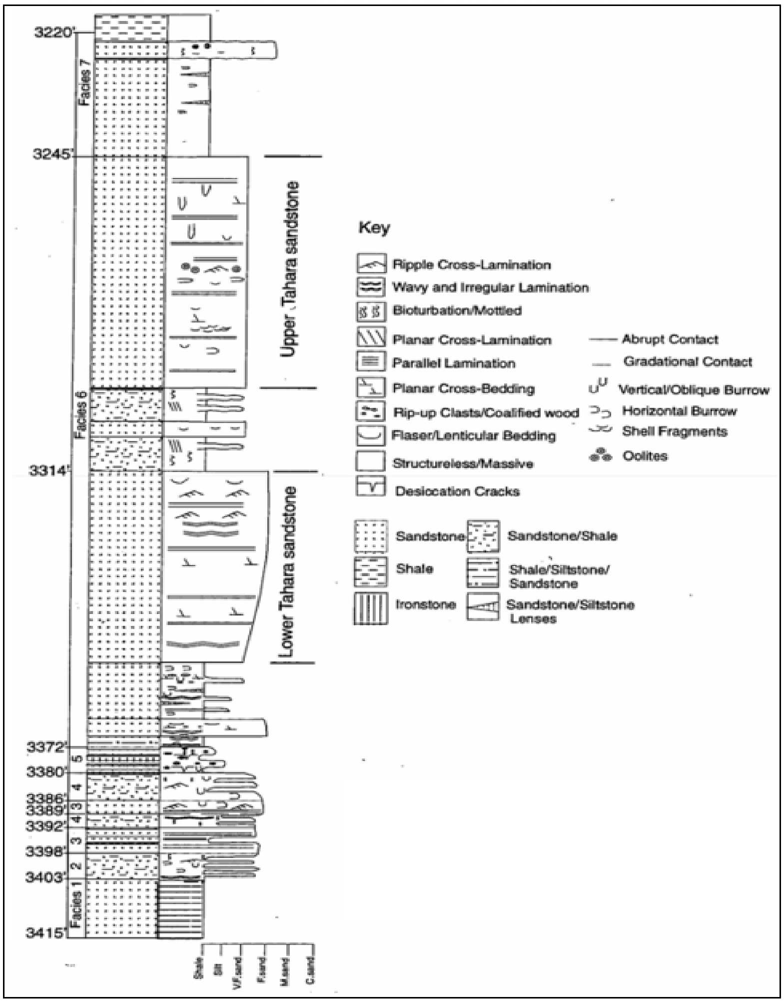

Figure 2: Lithology and sedimentary structures for the cored interval between 3220’ and 3415' in type well CI-49 (Burki 1998).

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Sequences and sequence boundary of the Tahara Formation

Sequence stratigraphy is defined as the study of rock relationships within a chronostratigraphic (time stratigraphic) framework of repetitive, genetically related strata bounded by surfaces of erosion or non-deposition or their correlative conformities (Van Wagoner et a/., 1988).

The detailed core examination (Burki 1998) and electric well-log correlation allow the recognition of two partial sequences (1 and 2) separated by a Type 1 sequence boundary (SB) of a lowstand palaeosol (Fig. 3). These sequences defined by correlation of strata using electric well log and core data are illustrated in Figure 3. Identification of a sequence boundary within the succession is based on the facies lithology. The sequence boundary was initiated during a fall of sea-level below the depositional shoreline break (Posamentier etal., 1988). This sequence boundary, however, is more difficult to pick away from type well CI-49 especially where core control is rare or absent. Below the sequence boundary is the preserved upper part of a highstand systems tract and above the sequence boundary is a transgressive systems tract with no preserved recognisable lowstand deposits (Fig. 3). The transgressive systems tract is bounded at the base by a laterally extensive Type 1 sequence boundary, and at its top by a maximum flooding surface.

Boundary is the upper part of a HST and above the sequence boundary is a TST with no recognised lowstand deposits. Classification based on stratal geometry and facies tracts.

The maximum flooding surface is overlain by the lower part of an incompletely exposed highstand systems tract. The maximum flooding surface consists of 2 m thick bioturbated sandstone containing rip-up clasts and shell fragments (Fig. 2). This material was deposited during a marine transgression and concentrated as a discrete bed on the top of the transgressive systems tract within sequence 2, in a marine-shelf environment (Fig. 3). Vertical stacking of these sequences is indicative of a transgressive-regressive event. Transgressive and regressive describe the direction of movement of the shoreline landward and seaward respectively (Reinson 1984; Posamentier and James 1993). The movement of the shoreline is a function of the balance between sediment supply and the space available on the shelf (accommodation).

Table 1: Description and interpretation of the facies recognized from the succession in the study are (Burki 1998)

Facies		Description	Interpretation
1. Lamination shale	Facies association	Black to dark-gray, micaceous, silty, horizontally laminated with sand and silt lenses, slightly bioturbated.	
2. Interlaminated to bioturbated shale (60%) and sandstone (40%)		Shale, dark-grey to yellowish-grey, horizontal to subhorizantal, wavy laminae. Sandstone is light grey, very fine grained, well sorted, laminated with symmetrical ripples and hummockey cross-stratification. Locally highly bioturbated (Skolithos, Chondrites).	
3. Parallel laminated and ripple cross-laminated sandstone.		Sandstone, fine to very fine-grained, carbonaceous, parallel laminae, locally massive, small-scale, low angle cross lamination interpreted as hummocky cross-stratification, parallel to subparallel lamination,waxy, interlaminated sandstone and mudstone, slightly bioturbated (Skolithos, Chondrites).	Shelf - Nearshore
4. Bioturbated sandstone and shale		Sandstone (75-60%), fine-grained, well sorted, mottled, laminated, flaser bedding, ripple profiles. Shale (25-40%), light brownish-grey, wavy, highly bioturbated (Skolithos or Arenicollites, Diplocraterion, Chondrites).	
5. Heterolithic		Ironstone, silty shale, mudstone, sandstone, varicoloured, bioturbated, oolitic, sideritic nodules, desiccation cracks.	Lagoonal periodic exposure
6. Planar cross bedded and horizontally laminated sandstone and shale.		Sandstone (80%), fine to very fine-grained, white, light grey, micaceous, carbonaceous, well sorted. Subordenate shale, dark grey to brownish-grey, highly micaceous and carbonaceous detritus. Subfacies (a) lower part, consists of shale with silt and sand laminae; some beds contain vertical and horizontal burrows. This package is overlain by horizontally laminated and structureless sandstone grading up into planar cross-bedded sandstone with small scale ripple cross-lamination and flaser type laminae. Subfaces (b) upper part, consists of interlaminated to bioturbated shale and sand followed by horizontally laminated, structureless and subordinate cross-bedded sandstone. Abundant shell fragments and skolithos, planolites, Chondrites. A subordinate, 80 cm thick muddy sandstone, contains carbonaceous material and ooids (mm's in diameter).	Shelf-Shoreface/Fluvio-deltaic (The later reported only from well C1-49). Shelf-Shoreline
7. Shale		Dark to medium dark gray, micaecous, pyritic, slightly bioturbated. A subordinate bioturbated sandstone bed containing shell fragments, rip-up clasts and oolites occurs.	Shelf

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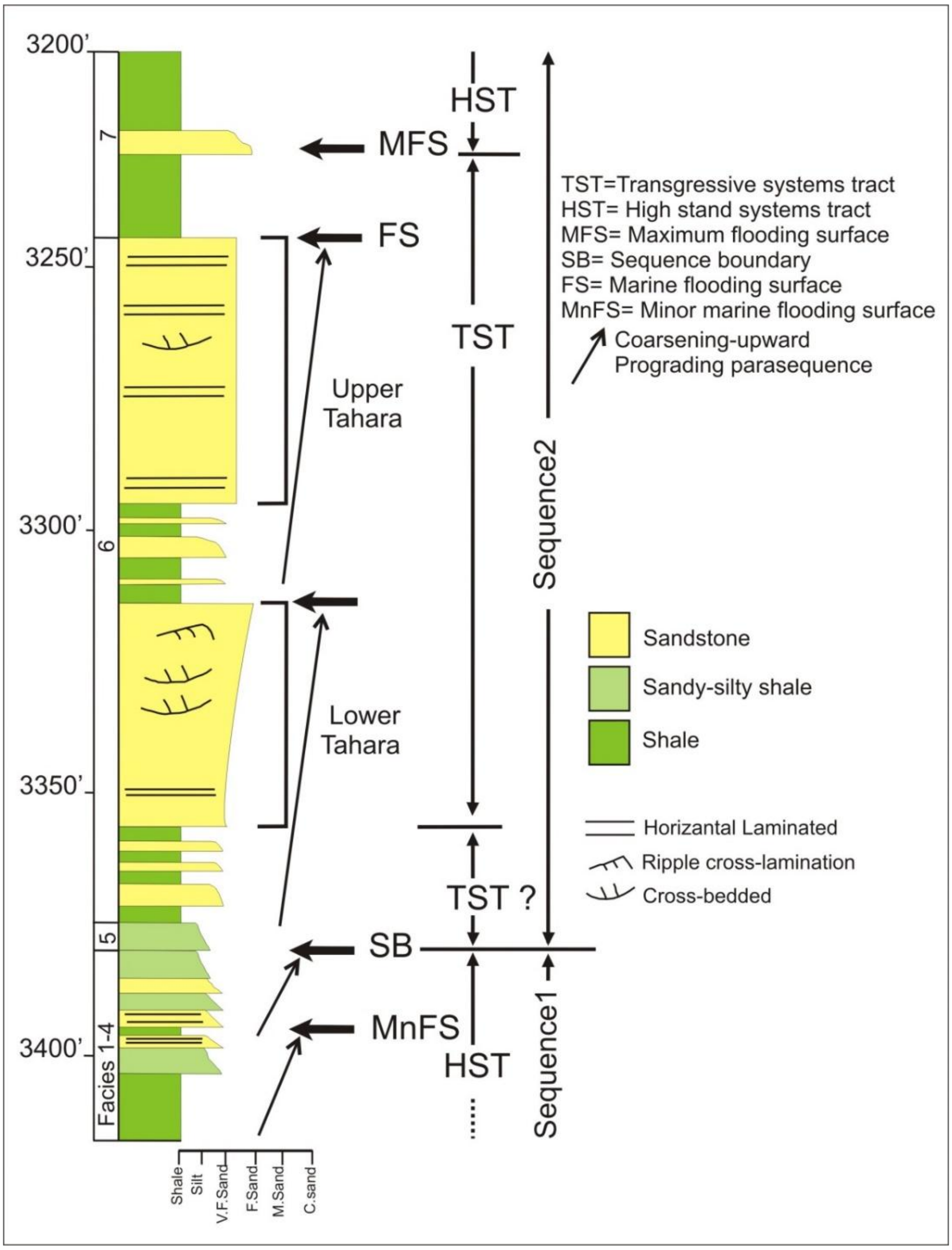

Figure 3: Detailed vertical succession illustrating two incomplete sequences separated by a lowstand (palaeosol) sequence boundary and systems tracts (highstand and transgressive systems tract) of the Tahara Formation from type well CI-49 below the sequence.

Sequence 1

The base of this sequence has not been cored, but is bounded at the top by a subaerial erosional surface, interpreted as a Type 1 sequence boundary (SB) (Van Wagoner et a., 1990), which clearly suggests a period of relative sea-level fall. The sediments present below this sequence boundary, represent the upper part of sequence 1 (Fig. 3). The core information shows it to be composed of a coarsening and upward thickening progradational succession. It consists of two pareasequences. The first parasequence is overlain by a subordinate thin shale bed which may have formed during minor transgression (relative sea-level rise), interpreted as a minor marine flooding event (Fig. 3). The second parasequence is truncated at the top by the sequence boundary defining the base of sequence 2.

Sequence 2

This incomplete, but better-preserved, sequence is deposited above the Type 1 sequence boundary and comprises transgressive and highstand systems tracts (Fig. 3). The most preserved part of this sequence consists of two coarsening-upward parasequences bounded at the top by marine flooding surfaces and at its base by the sequence boundary. The lower Tahara sandstone was deposited above these sediments and is followed by bioturbated sandstone and shale of the lower part of the upper parasequence, which passes upwards into the upper Tahara sandstone. The lower and upper Tahara sandstones extend laterally southwestwards away from type well CI-49 and will be discussed separately.

Lower Tahara

The lower sandbody consists of horizontally laminated and structureless sandstone overlain by planar cross-bedded sandstone showing an overall slight coarsening-upward trend (Fig. 3). This sandbody has been interpreted as a shoreface deposit overlain by fluvio-deltaic deposits in the upper part. The upward coarsening trend shows a gradation from shale to sandstone which is bounded at the top by a marine flooding surface defined by a transgressive marine shale. Flooding of the proceeding delta system and relative sea-level rise led to a low rate of sediment supply. The core available from well ATS2 shows well-preserved shoreface sands of the lower Tahara sandstone underlain by back-barrier deposits. It appears that the shoreline migrated landwards and that the sequence represents shoreface transgression under conditions of relative sea-level rise, high subsidence or minimal sediment supply and reworking of the shoreface sands (Galloway 1986; Elliott 1986b; Reading etal., 1996). Evidence of fluvial processes is negligible in the other four wells probably due to distance from the source. On the other hand Miall (1997) argued that delta deposits are rarely formed during transgression because the fluvial sediment supply tends to be influenced by the rise in base level i.e shifted landward. In addition, the preservation of fluvial sediments depends on the rate of sea-level rise, marine processes and sediment supply from hinterland tectonics (Reading and Levell 1996).

Upper Tahara

The vertical stacking pattern of the upper Tahara sandstone closely resembles the lower part of the lower Tahara sandstone, in that it consists of horizontal laminated and structureless sandstone. This sandstone has been attributed to shoreline progradation. The upper Tahara sandstone with the underlying marine shale represents another coarsening-upward parasequence. This progradational parasequence is also bounded at the top by a marine flooding surface and may have formed part of a transgressive systems tract during continuous sea-level rise. The middle part of the upper Tahara sandstone in well CI-49 contains 80 cm thick muddy sandstone. Thin-section analysis shows the presence of carbonaceous material, disseminated ooids, some of which are composed of feldspars, and high concentrations of glauconite and heavy minerals (Burki 2000). These sediments represent both shallow-marine and fluvially-influnced depositional systems. The presence of glauconite indicates a shallow-marine environment and deposition under anaerobic or reducing conditions (Pettijohn 1957), and low sedimentation rates (Reineck and Singh 1973; Tucker 1991). Thus, the appreciable spiky pattern through the gamma ray log values in the middle of the upper sandstone results from this high concentration of heavy minerals and glauconite in this part of the sandbody, feldspars and detrital shale. The transgressive systems tract is bounded at the top by 2 m thick bioturbated sandstone with lag deposits. This bed was deposited following transgression which occurred sufficiently slowly to allow time for reworking. The base of the bed is related to the time of maximum transgressive and it probably represents a maximum flooding surface (Vail et al., 1991), defining the contact between the transgressive systems tract and highstand systems tract above. Ancient prograding shorelines forming coarsening-upward sequences deposited during transgressive periods have been mentioned by many authors (e.g., Oomkens 1970; Reinson 1984; Elliott 1986b and others). There are three main factors that controlled the transgressive deposits attributed in this sequence: 1) relative rise in sea-level (Van Wagoner etal., 1990); 2) the succession is bounded at the top by a maximum marine flooding surface; and 3) change in rate of subsidence and sediment supply. The incompletely exposed marine shales and intercalated thin sandstone and siltstone laminae that overly the maximum flooding surface are interpreted to be related to progradation during deposition of the highstand deposits above (Fig. 3). It possibly records that part of the highstand systems tract (Van Wagoner et al., 1990) that was deposited during a subsequent rise in sea-level (Dalrymple 1992). As sea-level continued to rise water depth increases result in a decrease in clastic sediment supply concomitant with an increase in marine shale facies.

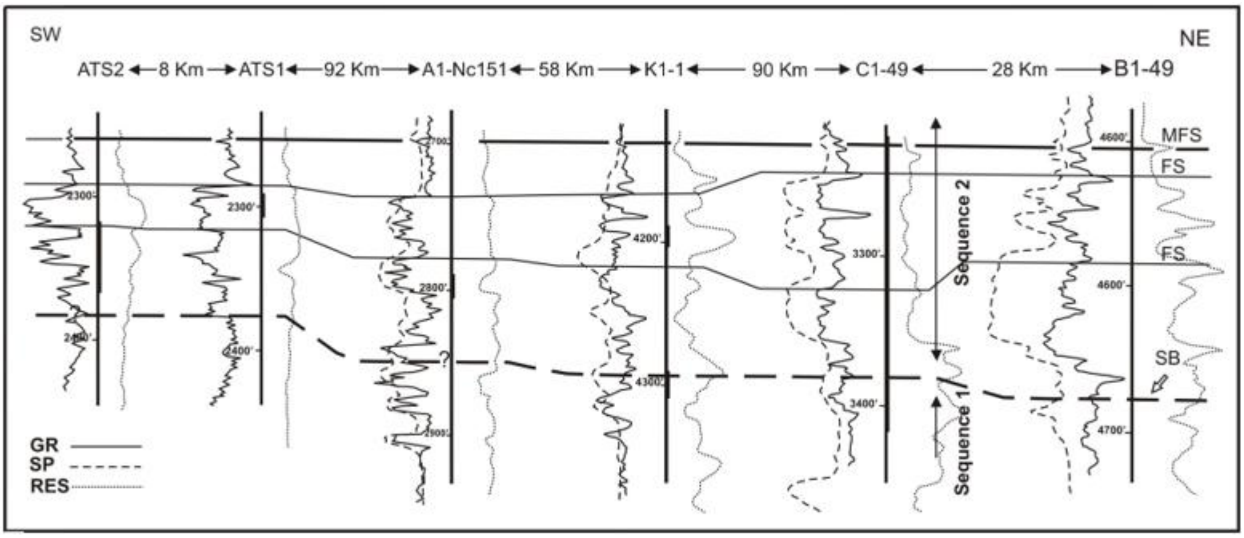

Figure 4: Stratigraphic cross-section along southwest-northeast trend. It represents the core and well log through the Tahara Formation. MFS (maximum flooding surface) used as datum line and vertical black bars indicate the cored intervals. FS represents marine flooding surface deposited during continuous sea level rise. Dashed line represents the sequence boundary (SB) of a regressive surface of erosion during sea-level fall (lowstand). The succession thins laterally southwesternwards. Note wireline log in well B1-49 is without scale

Sequence Stratigraphic from Wireline Log Trends

Identification of sequences from subsurface data depends upon the use of electric logs and seismic data. Wireline log patterns may be used to interpret depositional environments, and determine vertical sequence and bedding architecture. A wireline log trend suitable for lithology and stratigraphic interpretation is shown in Figures 5 and 6. It is essential to use both core and log data to interpret deposition environment and sequence stratigraphy.The interpretation of wireline log trends to identify falls and rises in relative sea-level is essential in order to show the sequence boundary, the maximum flooding surface and other minor marine flooding surface. Key sequence stratigraphic surfaces (sequence boundary, maximum flooding surface, and transgressive surface) that can be used to understand these surfaces in Tahara succession are listed below:

1) **Sequence boundaries (SB)** which result from a fall in relative sea-level may be difficult to recognize from the well log alone (Emery and Myer 1996). Rider (1996) claimed that there is no set of diagnostic responses, but evidence of a sequence boundary is its position in the sedimentary succession. The sequence boundary may represent abrupt upward change from progradation to retrogradation in the succession. A sequence boundary may result from an abrupt change in log response in sandstone units or may be marked by change in shale type in the shale section (Rider 1996). This surface is recognized only from core control from wells CI-49 and K1-1. In wireline log patterns between wells it proved more difficult to recognise because core data is lacking, and gamma ray signatures in this position are not clear in the other wells. The degree of similarity of the wireline log curves between wells decreases with increased distance between wells. However, a sequence boundary away from well K1-1 is proposed on the limited available evidence from the wireline logs (Fig. 6).
2) **A maximum flooding surface (MFS)** can be identified from a gamma ray peak (high gamma ray values) on bell and funnel trends respectively (i.e. where these are fining-upward and coarsening-upward respectively, the maximum flooding surface may be a gamma maximum). It should not be assumed that every gamma ray peak is a maximum flooding surface (Emery and Myer 1996). However, in core and well log data, the maximum flooding surface may be easily recognized by its distinct, relatively high gamma ray log values (Partington et al., 1993). Maximum flooding surface could be the surface above retrogradational and below progradationa! intervals. In the study area the maximum flooding surface is marked in the core by a bioturbated sandstone bed (well 01-49) and overlying deeper water shale environment, and could be easily recognized in wells without core control. This surface lies at the point of maximum gamma ray response and can be traced laterally into basinward settings where shale is separated by thin bioturbated sandstone (Fig 5). It correlates very well between wells, because the gamma ray signature of the maximum flooding surface has a more distinctive peak and forms a good marker horizon (used as datum line marker in cross-sections in this study).
3) **Marine flooding surfaces (FS)** as opposed to maximum flooding surface can be recognized from a sudden change in log value (abrupt increase in gamma ray reading). It indicates a change in lithology, such as shale resting sharply on sandstone. This surface typically terminates coarsening-upward trends. The example (Fig. 5) shows that the lower and/or upper Tahara sandstone was followed by transgressive marine shale that represents a parasequence, bounded at the top by a marine flooding surface. It can be easily correlated between wells. The facies successions are frequently bounded by this surface (Fig. 6).

Depositional System Tracts of the Tahara Succession from Wireline Logs

Recognition of the key sequence stratigraphic surfaces from the succession (Facies 1-7) described above allows the stratigraphy to be divided into parasequences which together form a systems tracts deposited during relative sea-level rise and fall. In this section an attempt will be made to identify these systems tracts from wireline log trends.

a) Progradation can be recognized from an upward decrease in gamma ray values resulting in an upward increase in grain-size (i.e. increase in sand/shale ratio). Progradation represents the funnel trends (Figs 5 and 6). The vertical pattern of upward coarsening and thickening reflects the progradational succession.
b) Retrogradation is indicated by fining-upward stacking patterns, which imply upward deepening (upward increase in gamma ray values). Retrogradation successions show vertical stacking patterns from sandstone to shale facies

Transgressive systems tract

From core examination (Fig. 2) shows two prominent sandstones which together with the underlying bioturbated sandstone and shale form two coarsening-upward parasequences. Two these parasequences are seen in the gamma ray log profile (Figs 5 and 6) emphasising the relationship between the core data and gamma ray log trends. Gamma ray log shapes in both sandstones are variable from funnel to roughly cylindrical shape (Cant 1984 b) as illustrated in Fig. 6. The log pattern from this Figure is not clearly defined in some cases. Cant (1983; 1984 b) shows an example from the Spirit River Formation, which has similar gamma log patterns to those in the lower sandstone in well ATS2, interpreted as irregular to cylindrical gamma ray log pattern. By contrast, "There is no simple pattern of mechanical log response that could be considered characteristic of subsurface transgressive shoreline deposits, because the variability of lithologies and contacts within a sequence is high" (Reinson 1984). The lower Tahara sandstone shows a serrate cylindrical gamma ray shape in well CI-49 and ATS2, and a funnel gamma ray shape in wells K1-1, A1-NC151 and ATS1. The upper Tahara sandstone shows funnel gamma ray shape in well CI -49 and well K1 -1 shows a complex gamma ray trend, whereas it shows a serrate cylindrical gamma ray log shape in well A1-NC151, ATS1 and ATS2 (Fig. 6). Both parasequences are bounded at their top by marine flooding surfaces, as indicated by a high gamma ray reading. Both parasequences represent a progradational pattern and these are reflected in the typical gamma ray log profiles. The serrate shape of gamma ray log patterns in parasequence sandstones is due to contrasting grain sizes within stratification and cross bedding. Parasequences represent the shoreline progradation setting. The vertical pattern of upward coarsening and thickening reflects the progradational deposits. Parasequences are part of sequence 2, deposited in transgressive systems tract in response to sea-level rise. This systems tract, is bounded at the top by a maximum flooding surface, and the bottom by a lowstand sequence boundary (Figs 5and 6).

Highstand systems tract

The lowermost part of the deposit below the sequence boundary consists of two small parasequences, separated by a minor marine flooding surface, both of which are recognized in core data. This package consists of facies 1-4 (Figure 2 and Table1) has been described and interpreted as shelf-nearshore environments. The parasequences are not evident on the wireline logs, the only evidence is an irregular shape followed by a funnel shape which reflects a gradual upward decrease in gamma ray value (After Cant 1984b). The irregular shape corresponds to the finer material (shale with subordinate sandstone and siltstone lamina of Facies 1) and may represent a deeper water setting.

Tahara Formation in Response to Sea-Level Changes

Gamma ray log correlation between wells in cross section (Fig. 6) shows an irregular trend followed by a funnel shape below the sequence boundary, especially in well CI-49. These shapes consist of shale with increase sand upward. This is interpreted to represent the coarsening-upward progradation part of the upper part of sequence 1 in response to sea-level rise followed by a fall. The upper and lower Tahara sandstones mostly show the funnel or cylindrical shapes but may be serrated, and the nature of the contacts are gradational or abrupt according to the gamma ray signatures (Fig. 6). Each sandstone with underlying transgressive marine shale shows gamma ray trends indicative of deposition along a prograding shoreline possibly in response to part of a third order relative sea-level rise (Fig. 5). The relative sea-level curve shows that the sequence 1 was deposited in the regressive phase followed by the transgressive phase of the incomplete sequence 2 (Fig. 6).

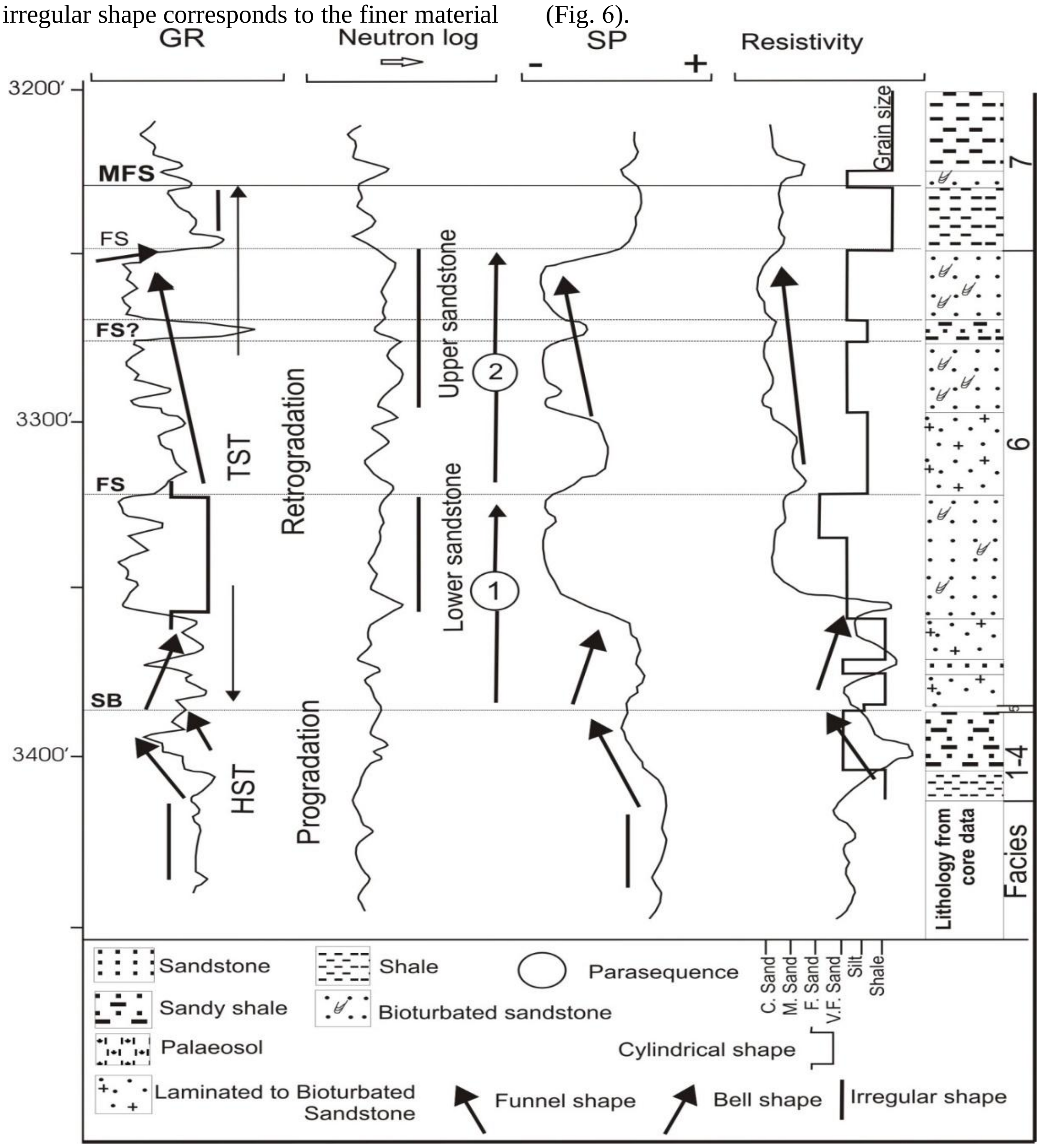

Figure 5: Wireline logs from type well C1-49. Gamma ray log (GR), self potential (SP), neutron (N) and resistivity log (Res) related to core lithology, and showing the trends in systems tracts, parasequences and key of stratigraphic surfaces in incomplete sequence 1 and 2.

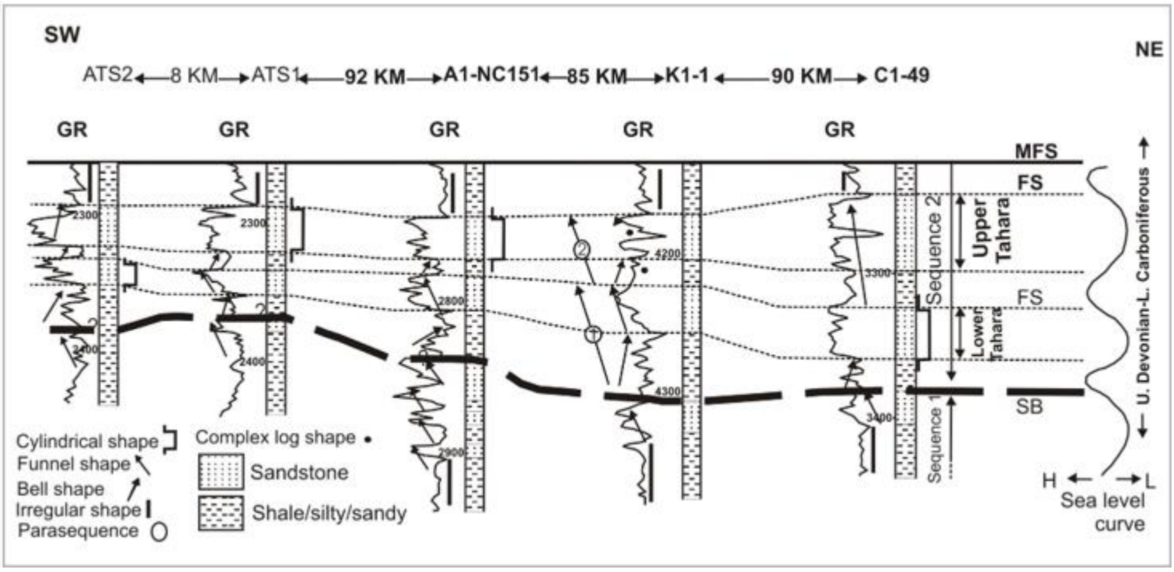

Figure 6: SW-NE well log cross section showing gamma ray trends between wells from incomplete sequence 1 and 2, and sea-level Curve based on the sequence stratigraphic interpretation. Lithologies recognized are based on core and log signatures.

3. Conclusions

The integration of wireline log and core data enhances understanding of the Tahara Formation's depositional systems and sequence stratigraphy. The study provides critical insights into the influence of sea-level changes on facies distribution, contributing significantly to petroleum reservoir evaluation in the Ghadamis Basin.

Devonian reservoirs have the best petrophysical properties on the southern basin flank but decrease in quality into the basin because of increased shaliness and diagenetic effects associated with deeper burial.

The facies pattern is different from one well to another, which does suggest that there was a strong tectonic control, that is differential tectonic subsidence and/or fault control, or that deposition was controlled by autocyclic processes.

The vertical stacking and repetition of similar facies patterns indicates a repetition of similar depositional processes. However, the succession was interrupted by episodic relative sea-level rises which produced repeated marine-shelf deposits. During tectonic activity the increased fluvial input, caused the depositional system to prograde seawards. This was followed by a gradual decrease in fluvial activity due to decreased tectonic activity and/or reduced source area relief through weathering and erosion. As a result marine transgression and a rise in relative sea-level occurred.

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